Protection and Polymerization of Functional Monomers. 28. Anionic Living Polymerization of Styrene Derivatives Containing Acetal-Protected Monosaccharide Residues

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ABSTRACT: Six styrene derivatives meta-substituted with acetal-protected glucofuranoses (**1**) and (**2**), galactopyranose (**3**), fructopyranose (**4**), and sorbofuranose (**5**) and para-substituted with acetal-protected glucofuranose (**6**) were synthesized by the Williamson reactions of *m*- or *p*-(chloromethyl)styrene with the corresponding protected monosaccharides in DMF and were anionically polymerized. The anionic polymerizations were carried out with *s*-BuLi in THF at −78 °C for 30 min. Among the monomers, **1**−**5**, were found to undergo anionic living polymerization to afford quantitatively the polymers of predictable molecular weights and narrow molecular weight distributions (M_w/M_n < 1.13). Novel well-defined block copolymers, polystyrene-*block*-poly(**1**) starting either from living polystyrene or the living polymer of **1**, were successfully synthesized. By contrast, no appreciable polymerization of **6** occurred under identical conditions.

Introduction

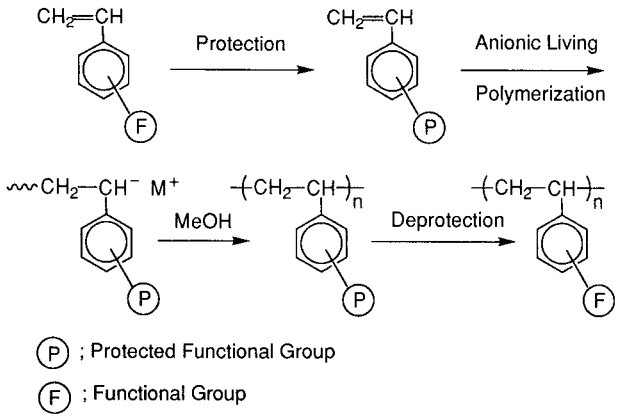
From a viewpoint of polymer synthesis, the technique of anionic living polymerization of conjugated hydrocarbon monomers such as styrene, 1,3-butadiene, and isoprene is undoubtedly the best established procedure to obtain polymers with controlled molecular weights and narrow molecular weight distributions. However, monomers with potentially useful functional groups are usually difficult to yield living polymers under the conditions of anionic polymerization. This is because these functional groups are normally incompatible with both anionic initiators and active propagating chain ends.

To overcome this difficulty, we have been developing, since 1982, a new and versatile strategy that involves protection and anionic living polymerization of functional monomers, followed by deprotection from the resulting polymers,[1−3] as shown in Scheme 1.

By means of this strategy, polystyrenes with a wide variety of functional groups (OH, SH, NH_2, CHO, COOH, $COCH_3$, and C≡CH) could be successfully synthesized by careful choice of the protecting group and setting the polymerization conditions. These polymers possessed well-controllable molecular weights and narrow molecular weight distributions and had functional groups in all monomer units. Furthermore, novel block copolymers having functional polymer segments could be synthesized. Thus, this strategy appeared to hold considerable promise for the synthesis of functional polymers with well-controlled architectures.

In the present study, as a part of our program to investigate the more generality of the above-mentioned strategy, we focus on the anionic living polymerization of styrenes containing monosaccharide residues. Generally speaking, the polymers containing saccharide residues are expected to have a variety of potential applications from the viewpoint of solubility in water, hydrophilicity, high water absorptivity, biodegradability, and pharmacological activity.[4−8] Furthermore, they would be used advantageously as chiral templates for

Scheme 1



asymmetric synthesis and optical resolution of organic compounds.[9,10] Because of such potential applications, there have been many reports on such applications of various polymers containing saccharide residues usually prepared by free radical polymerization of the corresponding monomers and by means of polymer reactions.

Very recently, some attempts to synthesize polymers containing mono- and/or oligosaccharide residues with well-defined structures by means of living polymerization have been reported. For example, Schrock and Nomura have reported Mo-catalyzed living methathesis polymerization of norbornane derivatives containing protected monosaccharides. Well-controlled homopoly(norborene)s and block poly(norbornene)s having monosaccharide residues as side chains were successfully obtained.[11] Miyamoto and co-workers have applied the methods of cationic and radical living polymerizations to the preparation of poly(vinyl ether)s and polystyrenes with pendant mono- or oligosaccharide residues.[12−14] However, such studies on the living polymerization are still quite limited, and to the best of our knowledge, there has been no previous study on the anionic living polymerization so far.

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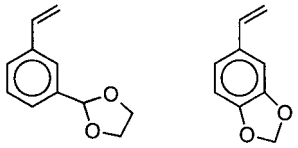
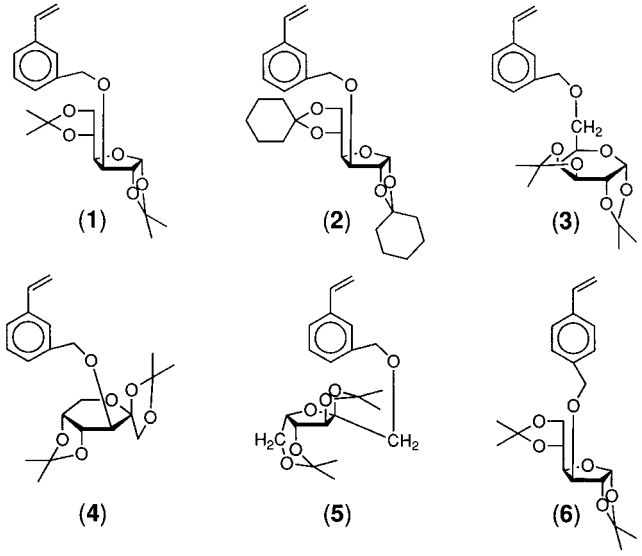
To realize the anionic living polymerization of the styrenes containing monosaccharide residues, their hydroxy groups must be protected prior to the polymerization. Among a number of known protecting groups, acetal would be the most suitable choice for our purpose, since we have demonstrated that the following styrene derivatives containing acetal-protected functionalities undergo anionic living polymerization without problems,[15,16] and it is needless to say that acetal protecting groups can quite easily be removed afterward in acid conditions.[8,17]



In this paper, we present the anionic living polymerizations of the following styrene derivatives meta-substituted with acetal-protected glucofuranoses (**1**) and (**2**), galactopyranose (**3**), fructopyranose (**4**), and sorbofuranose (**5**). In addition, we also examine the anionic polymerization behavior of the para-substituted isomeric monomer of **1** (**6**).



Experimental Section

Materials. 4-(Chloromethyl)styrene, supplied from Seimi Chemical Co. Ltd., was used for the synthesis of **6** without purification. Styrene was distilled over calcium hydride and further purified by distillation in the presence of phenylmagnesium chloride (THF solution) on a vacuum line. THF used as a polymerization solvent was refluxed over sodium wire for 5 h and distilled from lithium aluminum hydride and finally through a vacuum line from the sodium naphthalenide solution.

Initiators. Commercially available *s*-BuLi as a 1.05 M solution in cyclohexane was used without purification and diluted with *n*-heptane. Potassium naphthalenide was prepared by the reactions of a small excess amount of naphthalenide with potassium in dry THF at room temperature for 10 h. The concentration of potassium naphthalenide thus prepared was determined from a green color to colorless endpoint change by colorimetric titration with standardized 1-octanol in a sealed reactor under high-vacuum conditions.[18] It was stored at −30 °C in ampules equipped with breakseals and used for the polymerization within 1 week.

3-Bromobenzyl Alcohol. 3-Bromobenzyl alcohol was prepared by the reduction of 3-bromobenzaldehyde with $NaBH_4$. To a solution of $NaBH_4$ (3.19 g, 84.2 mmol) in ethanol (150 mL) was added dropwise 3- bromobenzaldehyde (30.0 g, 162 mmol) at 0 °C. The mixture was allowed to warm slowly to room temperature and stirred for 3 h. It was then cooled to 0 °C and acidified by slow addition of 2 *N* HCl. The organic layer was separated, and the aqueous layer was extracted three times with diethyl ether. The combined organic extracts were washed with water, dried over $MgSO_4$, and concentrated under reduced pressure to afford crude 3-bromobenzyl alcohol (30.4 g, 162 mmol, 100%) as a pale yellow liquid. It was used in the further reaction without purification: ^{1}H NMR ($CDCl_3$) δ 7.43−7.20 (m, 4H, Ar), 4.67 (s, 2H, CH_2O−), 1.83 (s, 1H, OH).

3-Bromo(methoxymethyl)benzene. To a stirred solution of 3-bromobenzyl alcohol (30.2 g, 161 mmol) in 120 mL of dry dimethylformamide (DMF) was added sodium hydride (7.73 g, 322 mmol) in small portions at 0 °C, and the mixture was stirred for 30 min at room temperature. Methyl iodide (19.8 mL, 322 mmol) was then added dropwise to the mixture at 0 °C, and the mixture was stirred at room temperature overnight. It was quenched with 700 mL of water and extracted with diethyl ether. The combined organic layer was washed with water, dried over $MgSO_4$, and concentrated. Fraction distillation at 70−71 °C (3 Torr) gave a colorless liquid (28.2 g, 140 mmol, 87%): ^{1}H NMR ($CDCl_3$) δ 7.42−7.21 (m, 4H, Ar), 4.42 (s, 2H, CH_2O-), 3.41 (s, 3H, OCH_3).

3-(Methoxymethyl)benzaldehyde. To a solution of the Grignard reagent from 3-bromo(methoxymethyl)benzene (8.50 g, 42.1 mmol) and Mg (2.29 g, 94.3 mmol) in THF (90 mL) was added carefully dropwise DMF (23.0 mL, 297 mmol) at 0 °C. The solution was allowed to warm to room temperature and stirred for an additional 3 h. After the standard workup, fractional distillation of the crude product at 65−70 °C (1.5−2.0 Torr) gave 3-(methoxymethyl)benzaldehyde as a colorless liquid (4.51 g, 30.1 mmol, 71%): ^{1}H NMR ($CDCl_3$) δ 7.80−7.50 (m, 4H, Ar), 4.53 (s, 2H, CH_2O-), 3.43 (s, 3H, OCH_3), 10.03 (s, 1H, CHO).

3-(Methoxymethyl)styrene. To a solution of methyltriphenylphosphonium bromide (12.7 g, 35.6 mmol) and potassium *tert*-butoxide (5.00 g, 44.6 mmol) in THF (30 mL) was added dropwise a portion of 3-(methoxymethyl)benzaldehyde (4.47 g, 29.8 mmol) at 0 °C under a nitrogen atmosphere. The reaction mixture was kept at 0 °C with stirring for 2 h. The mixture was poured into water to quench the residual potassium *tert*-butoxide, followed by extraction with diethyl ether. The organic layer was washed with water and dried over $MgSO_4$. After the ether had been evaporated, fractional distillation gave 3.99 g (26.9 mmol) of 3-(methoxymethyl)-styrene as a colorless liquid in 90% yield (bp 69−70 °C/4.0 Torr): ^{1}H NMR ($CDCl_3$) δ 7.36−7.21 (m, 4H, Ar), 6.72 (dd, 1H, −CH═), 5.77, 5.25 (2d, 2H, J = 17.6 and 10.9 Hz, CH_2═), 4.46 (s, 2H, CH_2O−), 3.40 (s, 3H, OCH_3).

3-(Chloromethyl)styrene. To a CCl_4 solution of 3.88 g (26.2 mmol) of 3-(methoxymethyl)styrene was added dropwise at 0 °C boron trichloride in CH_2Cl_2 (1.0 M, 28.6 mL). The resulting reaction mixture was maintained at 0 °C for an additional 2 h, and excess boron trichloride was then destroyed by careful addition of a slight excess (1.5 mL) of methanol. The solution was poured slowly into a stirred solution of 160 mL of 5% NaOH containing 110 g of ice. The organic layer was separated and the aqueous layer extracted with CCl_4 (2 × 15 mmol). Combined extracts were washed with water and dried over $MgSO_4$. A pure product (2.91 g, 19.1 mmol) was obtained in 73% yield by fractional distillation at 78−79 °C/2 Torr: ^{1}H NMR ($CDCl_3$) δ 7.42−7.26 (m, 4H, Ar), 6.71 (dd, 1H, −CH═), 5.77, 5.28 (2d, 2H, J = 17.7 and 11.1 Hz, CH_2═), 4.59 (s, 2H, CH_2Cl).

***m*-(1,2:5,6-Di-*O*-isopropylidene-α-D-glucofuranose-3-oxymethyl)styrene (1).** 1,2:5,6-Di-*O*-isopropylidene-α-D-glucofuranose[19] (2.50 g, 9.65 mmol) was dissolved in 15 mL of dry DMF and was treated with 0.28 g (11.7 mmol) of sodium hydride at room temperature for 2 h. 3-(Chloromethyl)styrene (1.40 g, 9.19 mmol) was added gradually to the mixture. The reaction mixture was heated in an oil bath at 50 °C for 6 h.

The solution was transferred into a separatory funnel together with 30 mL of benzene and was extracted with four 10-mL portions of water. The organic layer was dried over $MgSO_4$ and concentrated. **1** was isolated by flash column chromatography on silica gel (hexanes/EtOAc, 8.5/1.5 v/v) to afford 3.01 g (7.98 mmol, 87%) as a colorless syrup. **1** thus obtained was carefully freeze-dried several times to remove a trace of water from the benzene solution: ^{1}H NMR ($CDCl_3$) δ 7.39−7.25 (m, 4H, Ar), 6.70 (dd, 1H, −CH═), 5.90 (d, 1H, J = 3.69 Hz, α-furanose H-1), 5.76, 5.26 (2d, 2H, J = 17.6 and 11.0 Hz, CH_2═), 4.66 (d, 2H, J = 7.98 Hz, benzyl −CH_2-), 4.60−4.01 (m, 6H, H-2−H-6), 1.49, 1.43, 1.37, and 1.31 (four singlets, 12H, CH_3).

***m*-(1,2:5,6-Di-*O*-cyclohexylidene-α-D-glucofuranose-3-oxy-methyl)styrene (2), *m*-(1,2:3,4-Di-*O*-isopropylidene-α-D-galactopyranose-6-oxy-methyl)styrene (3), *m*-(1,2:4,5-Di-*O*-isopropylidene-*β*-D-fructopyranose-3-oxy-methyl)styrene (4), and *m*-(2,3:4,6-Di-*O*-isopropylidene-*β*-L-sorbofuranose-1-oxy-methyl)styrene (5). 2−5** were synthesized in good yields by a procedure similar to that used for **1**. 1,2:5,6-di-*O*-cyclohexylidene-α-D-glucofuranose,[20] 1,2:3,4-di-*O*-isopropylidene-α-D-galactopyranose,[21] 1,2:4,5-Di-*O*-isopropylidene-*β*-D-fructopyranose,[22] or 2,3:4,6-di-*O*-isopropylidene-*β*-L-sorbofuranose[23] was used in each of the reactions. After the usual workup, flash column chromatography on silica gel (hexanes/EtOAc, 8.5/1.5 v/v) afforded **2**, **3**, or **4** as a colorless syrup or **5** as a white solid with a low melting point near room temperature (ca. 20 °C).

2: ^{1}H NMR ($CDCl_3$) δ 7.38−7.26 (m, 4H, Ar), 6.72 (dd, 1H, −CH═), 5.90 (d, 1H, J = 3.60 Hz, α-furanose H-1), 5.75, 5.26 (2d, 2H, J = 17.7 and 11.1 Hz, CH_2═), 4.68 (d, 2H, J = 3.60 Hz, benzyl −CH_2−), 4.59−3.98 (m, 6H, H-2−H-6), 1.72−1.27 (m, 20H, cyclohexanes).

3: ^{1}H NMR ($CDCl_3$) δ 7.40−7.23 (m, 4H, Ar), 6.71 (dd, 1H, −CH═), 5.55 (d, 1H, J = 4.80 Hz, α-pyranose H-1), 5.76, 5.24 (2d, 2H, J = 17.7 and 11.1 Hz, CH_2═), 4.60 (s, 2H, benzyl −CH_2−), 4.57−3.63 (m, 6H, H-2−H-6), 1.54−1.34 (m, 12H, CH_3).

4: ^{1}H NMR ($CDCl_3$) δ 7.42−7.26 (m, 4H, Ar), 6.70 (dd, 1H, −CH═), 5.74, 5.24 (2d, 2H, J = 17.6 and 10.8 Hz, CH_2═), 4.97, 4.65 (2d, 2H, J = 12.0 and 12.3 Hz, benzyl −CH_2−), 4.41−3.49 (m, 7H, *β*-pyranose H-1−H-6), 1.54, 1.50, 1.43, and 1.39 (four singlets, 12H, CH_3).

5: ^{1}H NMR ($CDCl_3$) δ 7.41−7.26 (m, 4H, Ar), 6.67 (dd, 1H, −CH═), 5.74, 5.24 (2d, 2H, J = 17.7 and 10.8 Hz, CH_2═), 4.72, 4.59 (2d, 2H, J = 12.3 and 12.3 Hz, benzyl −CH_2−), 4.52−3.72 (m, 7H, *β*-furanose H-1−H-6), 1.56−1.29 (m, 12H, CH_3).

***p*-(1,2:5,6-Di-O-isopropylidene-α-D-glucofuranose-3-oxymethyl)styrene (6). 6** was synthesized in a procedure similar to that used for **1**. 4-(Chloromethyl)styrene was used in this reaction. After the usual workup, flash column chromatography on silica gel (hexanes/EtOAc, 8.5/1.5 v/v) afforded **6** as a colorless syrup (yield 88%): ^{1}H NMR ($CDCl_3$) δ 7.41−7.29 (m, 4H, Ar), 6.70 (dd, 1H, −CH═), 5.90 (d, 1H, J = 3.60 Hz, α-furanose H-1), 5.75, 5.25 (2d, 2H, J = 17.7 and 10.8 Hz, CH_2═), 4.65 (d, 2H, J = 5.10 Hz, benzyl −CH_2−), 4.59−4.01 (m, 6H, H-2−H-6), 1.49, 1.43, 1.38, and 1.31 (four singlets, 12H, CH_3).

Polymerization Procedures. All polymerizations were carried out in THF at −78 °C in an all-glass apparatus equipped with breakseals with vigorous shaking under high-vacuum conditions, as previously reported.[18] The polymerization was in situ terminated with degassed methanol or 1-octanol at −78 °C. The reaction mixture was poured into a large excess of hexane to precipitate a polymer. The resulting polymer was purified by reprecipitation in THF/hexane and by freeze-drying from the benzene solution.

Block Copolymerization. In all-glass apparatus in vacuo, the first-stage polymerization of **1** was initiated with *s*-BuLi in THF at −78 °C. After 30 min, a small portion of the living prepoly(**1**) was withdrawn to a small tube attached to the side of the apparatus for determining the M_n and M_w/M_n of the first-stage polymer. To the residue of the polymerization mixture was added styrene in THF at −78 °C in one portion with vigorous stirring, and the second-stage polymerization was continued for an additional 30 min. Both polymer solutions were in situ terminated via breakseals with degassed methanol at the same time. The polymers were quantitatively obtained in both cases. Similarly, the sequential copolymerization of styrene and **1** by the reversed addition of both monomers was carried out to quantitatively afford a well-defined block copolymer.

Table 1. Anionic Polymerization of 1 in THF at −78 °C for 0.5 h[a]

initiator mmol	monomer mmol	$10^{-3}M_n$ calcd[b]	$10^{-3}M_n$ obsd[c]	M_w/M_n[d]
s-BuLi, 0.121	2.38	7.5	6.3	1.09
s-BuLi, 0.0787	2.29	11	9.3	1.07
s-BuLi, 0.0364	3.00	31	33[e]	1.08
s-BuLi, 0.0203	2.38	70	82[f]	1.13

[a] Yields of polymers were quantitative in all cases. [b] M_n(calcd) = ([monomer] × (MW of monomer)/[initiator] + MW of initiator. [c] M_n(obsd) of the polymers with M_n(calcd) ≤ 20 × 10^3 were estimated by ^{1}H NMR area ratio of signals corresponding to the main chain and initiator fragment. M_n(obsd) of the polymers with M_n(calcd) > 20 ×10^3 were calculated from M_w by SLS and M_w/M_n by SEC. [d] M_w/M_n was estimated from SEC calibration by using standard polystyrenes in THF solution. [e] dn/dc = 0.101 (in DMF). [f] dn/dc = 0.120 (in DMF).

Measurements. ^{1}H NMR spectra were recorded on a Bruker DPX spectrometer operating at 300 MHz in $CDCl_3$. Chemical shifts were reported in ppm downfield relative to tetramethylsilane (δ 0) as standard. Size-exclusion chromatography (SEC) was performed on a TOSOH HLC 8020 instrument with UV (254 nm) and refractive index detection. THF was used as a carrier solvent at a flow rate of 1.0 mL/min. Three polystyrene gel columns (TOSOH G5000H_{XL}, G4000H_{XL}, and G3000H_{XL}) were used. Calibration curves were made to determine M_w/M_n values with standard polystyrene samples. Polymer (5 mg) was dissoved in 1 mL of THF, and the solution was injected. Laser light scattering measurements were performed with an Ootsuka Electronics DSL-600R instrument in DMF for polymers of **1**, **3**, **4**, and **5** and $CHCl_3$ for poly(**2**). The values of dn/dc were in the range 0.090−0.120 in DMF, while the dn/dc for poly(**2**) in $CHCl_3$ was 0.141.

Results and Discussion

Anionic Polymerization of 1. A series of the anionic polymerization of **1** were carried out at various monomer-to-initiator ratios in THF at −78 °C. *s*-BuLi was used as an initiator. When **1** was mixed with *s*-BuLi, the immediate appearance of a reddish orange color possibly for the polystyryl anion derived from **1** was observed. This color remained unchanged during the course of the polymerization but disappeared by quenching with a few drops of degassed methanol, as expected. Yields of polymers were always quantitative. The results are summarized in Table 1.

In all cases, SEC curves of the resulting polymers revealed unimodal peaks and narrow molecular weight distributions, M_w/M_n values being 1.07−1.13 based on the standard polystyrene calibration curve. Their M_n values were determined by ^{1}H NMR ($M_n \leq 20 \times 10^3$) from the peak intensities of initiator fragment (the methyl groups of *sec*-butyl group) and those of main chains or side chains and by static light scattering (SLS) measurement ($M_w > 20 \times 10^3$).

Unfortunately, **1** was a viscous liquid and could be neither distilled nor recrystallized. **1** was therefore purified by column chromatography and freeze-dried several times (usually three times) from the benzene solution under high vacuum condition. With the use of these monomers in the anionic polymerization, the M_n's of the resulting polymers were found to agree well with those calculated in the cases where the M_n's were less

Table 2. Block Copolymerization of 1 with Styrene in THF at −78 °C[a]

first monomer	second monomer	block copolymer (homopolymer[b]) $10^{-3}M_n$ calcd[c]	obsd[d]	M_w/M_n[e]
1	styrene	15 (7.5)	14 (6.3)	1.09 (1.09)
styrene	**1**	11 (4.8)	9.9 (4.8)	1.09 (1.06)

[a] Yields of polymers were quantitative in all cases. [b] Homopolymers were obtained at the first-stage polymerization. [c] M_n(calcd) = ([monomer] × (MW ofmonomer)/[initiator] + MW of initiator. [d] The molecular weights of the block copolymers were determined by using the molecular weights of the homopolymers and the molar rations of monomer units in the block copolymer and analyzed by ^{1}H NMR. [e] M_w/M_n was estimated from SEC calibration by using standard polystyrenes in THF solution.

than 20 000. In the polymer samples with the M_n's of more than 20 000, however, the observed M_n values are always definitely higher than those calculated.

As will be described in the details afterward, a well-defined block copolymer is successfully synthesized by the sequential addition of **1** at first and then styrene. Furthermore, all the polymers obtained with *s*-BuLi possessed narrow molecular weight distributions, as was seen in Table 1. These results strongly suggest that neither termination nor transfer reaction occurs during the course of and after the polymerization. Accordingly, the cause for deviating M_n values from those calculated may possibly be due to the reaction between *s*-BuLi, and the impurities in **1** occurred at the initiation stage of the polymerization. We therefore in situ titrated the red polymer solutions with standardized 1-octanol in THF to a colorless end-point to determine the actual amounts of living carbanionic chain ends surviving after the polymerization. The M_n's were then recalculated by using these titrated values instead of *s*-BuLi used in the polymerization. The M_n values thus recalculated are found to be good in agreement with those observed by SLS. Thus, our assumption may be reasonable.

These results as well as the appearance of the characteristic reddish orange color indicate strongly the living character of the polymerization of **1**. Accordingly, both the isopropylidene protecting groups and glucofranose framework of **1** are sufficiently stable under the condition of anionic living polymerization in THF at −78 °C.

Block Copolymerization of 1 with Styrene. Generation of the living polymer of **1** enables us to synthesize novel block copolymers having predictable main chain architecture. The result of block copolymerization also provides information concerning the stability of the living polymer of **1** as well as reactivities of **1** and the living polymer. A block copolymerization was carried out with *s*-BuLi in THF at −78 °C by sequentially adding **1** at first and then styrene. A polymer was obtained quantitatively. The results are summarized in Table 2.

As you can see in Figure 1, the SEC curve of the resulting polymer shifted completely toward the higher molecular weight side after the addition of styrene. The M_n(obsd) was fairly consistent with that calculated, and the distribution was narrow (M_w/M_n = 1.09). The composition of each polymer segment determined by ^{1}H NMR agreed with the feed ratio of **1** and styrene. These results clearly show that the block copolymerization of **1** with styrene successfully proceeds to afford a well-defined poly(**1**-*b*-styrene) of AB diblock copolymer. It should be emphasized that the success of this block copolymerization provides a direct evidence for the living character of the polymerization of **1**.

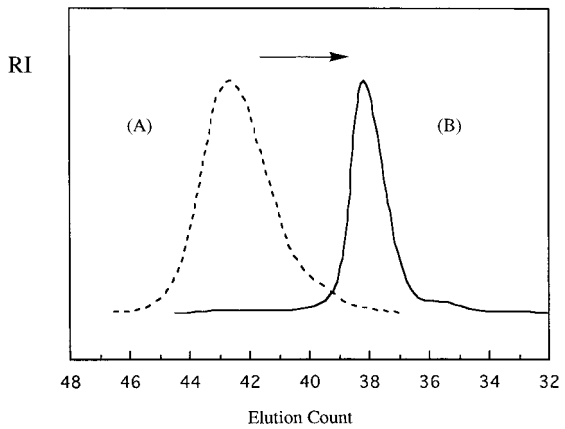


Figure 1. SEC curves of poly(**1**) at the first-stage polymerization (A) and of poly(**1**-*b*-styrene) obtained by the second-stage polymerization (block copolymerization) (B): peak A, M_n(calcd) = 7500, M_n(obsd) = 6300, M_w/M_n = 1.09; peak B, M_n(calcd) = 15 000, M_n(obsd) = 14 000, M_w/M_n = 1.09. (The second monomer was added after the first-stage polymerization for 0.5 h.)

By changing the addition order of two monomers where styrene and **1** were sequentially added in this order, a well-defined poly(styrene-*b*-**1**) could also be synthesized quantitatively. Thus, both sequential addition methods are possible in synthesizing block copolymers of **1** and styrene, indicating that reactivities of **1** and the living polymer are similar to those of styrene and living polystyrene.

Anionic Polymerizations of 2−5. In this section, the four structurally analogous styrene monomers, **2**−**5**, were newly synthesized and anionically polymerized under the identical conditions employed in the case of **1**. These monomers, **2**−**4**, were viscous liquids, although **5** was a white solid with a low melting point near room temperature. Similar to **1**, they could neither distilled nor recrystallized. They were purified by column chromatography and freeze-dried three to five times from their benzene solutions under high-vacuum conditions.

At first, having the monomer **2** meta-substituted with dicyclohexylidene α-D-glucofuranose residue in hand, we attempted to carry out the polymerization with *s*-BuLi in THF at −78 °C for 0.5 h. Similar to the polymerization of **1**, the immediate appearance of a reddish orange color was observed on mixing **2** with *s*-BuLi. Polymer yields were quantitative. The results are summarized in Table 3. The resulting polymers all had symmetrical SEC distributions composed of unimodal peaks and were narrow in molecular weight. They were observed to have predictable M_n values. Thus, obviously, the polymerization of **2** proceeded in a living manner. We also found from the results that the cyclohexylidene protection showed sufficient stability under the condition of anionic living polymerization of **2**.

Similarly, the anionic polymerizations of **3**−**5** were carried out under the same conditions. Again, a reddish orange color was developed instantaneously on mixing the monomer with *s*-BuLi in each of all cases. Yields of polymers were quantitative in all cases. The results are also listed in Table 3. The resulting polymers all had unimodal SEC single peaks and narrow molecular weight distributions. They possessed well-controlled molecular weights, although the values of M_n calculated were recalculated by the in situ titrated values as mentioned before in the polymerization of **1** in the cases where the polymer samples possessed molecular weights

Table 3. Anionic Polymerization of 2, 3, 4, and 5 in THF at −78 °C for 0.5 h[a]

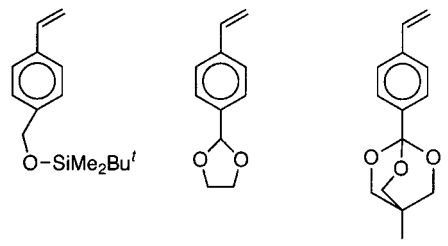
monomer	s-BuLi mmol	monomer mmol	$10^{-3}M_n$ calcd[b]	$10^{-3}M_n$ obsd[c]	M_w/M_n[d]
2	0.181	1.94	4.8	5.5	1.03
	0.0886	1.98	10	9.5	1.05
	0.0485	2.02	19	26[e]	1.07
3	0.210	2.00	3.6	3.2	1.06
	0.0715	2.08	11	9.4	1.08
	0.0184	2.17	48	57[f]	1.13
4	0.0760	2.01	10	8.5	1.07
	0.0381	2.02	20	16[g]	1.07
5	0.0924	2.69	11	9.3	1.08
	0.0377	2.50	25	20	1.07
	0.0281	2.69	36	32[h]	1.09

[a] Yields of polymers were quantitative in all cases. [b] M_n(calcd) = ([monomer] × (MW of monomer)/[initiator] + MW of initiator. [c] M_n(obsd) of the polymers with M_n(calcd) ≤ 20 × 10^3 were estimated by the ^{1}H NMR area ratio of signals corresponding to the main chain and initiator fragment. M_n(obsd) of the polymers with M_n(calcd) > 20 × 10^3 were calculated from M_w by SLS and M_w/M_n by SEC. [d] M_w/M_n was estimated from SEC calibration by using standard polystyrenes in THF solution. [e] dn/dc = 0.141 (in chloroform). [f] dn/dc = 0.111 (in DMF). [g] dn/dc = 0.090 (in DMF). [h] dn/dc = 0.099 (in DMF).

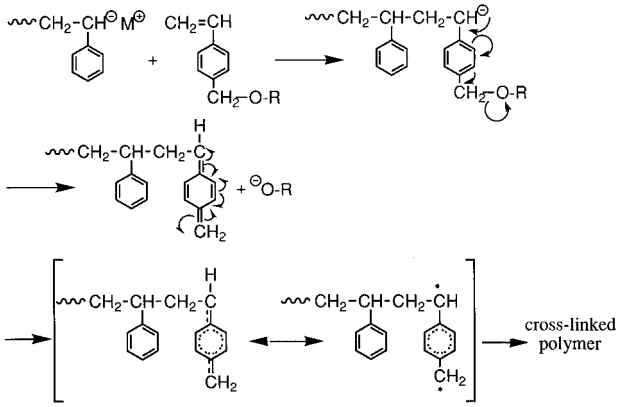
higher than 20 000. Accordingly, on the basis of these results as well as red coloration in all systems, the anionic polymerizations of **3**−**5** are indicated to proceed in a living manner. Thus, the protected functionalities by isopropylidene as well as cyclohexylidene groups and various monosaccharide frameworks including α-D-glucofuranose, α-D-galactopyranose, β-D-fructopyranose, and β-L-sorbofuranose are quite robust and able to survive completely under the conditions of anionic living polymerization.

Anionic Polymerization of 6. In contrast to successful living polymerizations of **1**−**5** that are meta-substituted styrene derivatives, attempts to polymerize **6** of the para isomer of **1** failed with the use of either *s*-BuLi or potassium naphthalenide. No polymer was obtained in each case. Furthermore, an anomalous behavior of **6** was observed in the block polymerization of **6** with the difunctional living polystyrene prepared from styrene and potassium naphthalenide. In this case, an insoluble gelatinous material was formed, along with a small amount of soluble polymer with a very broad molecular weight distribution. The insoluble material may be a cross-linked polystyrene where only a few units of **6** are included, since it is insoluble in organic solvents and has a IR spectrum very similar to that of polystyrene. In addition, **6** unreacted was recovered considerably. Accordingly, **6** did not participate in the polymerization with difunctional living polystyrene but would be responsible for cross-linking of difunctional living polystyrene.

These results of the polymerizations of **6** with anionic initiators and with difunctional living polystyrene are very similar to those of the following styrene derivatives, which possess benzyl ether skeletons previously reported by our group:[15,24,25]



Scheme 2



We therefore proposed the following reaction pathway that the carbanion at the chain end induced 1,6-elimination to generate a very reactive *p*-xylylene or biradical intermediate, which might react readily with each other to result in an insoluble cross-linked polymer, as shown in Scheme 2.

The results of the anionic polymerization of **6** can be reasonably explained by this reaction pathway. Notice that this pathway can be applied to para- and possibly ortho-substituted monomers, but not the corresponding meta-substituted isomers.

Conclusions

The anionic living polymerizations of various styrene monomers containing acetal-protected monosaccharide residues, **1**−**5**, were achieved successfully with *s*-BuLi in THF at −78 °C. These monomers were five styrene derivatives meta-substituted with diisopropylidene-α-D-glucofuranose, dicyclohexylidene-α-D-glucofuranose, diisopropylidene-α-D-galactopyranose, diisopropylidene-β-D-fructopyranose, and diisopropylidene-β-L-sorbofuranose residues. On the other hand, it was found that no appreciable polymerization of **6** of the para-substituted monomer occurred under exactly the same condition.

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